A Shapley Value Perspective on ISP Settlements

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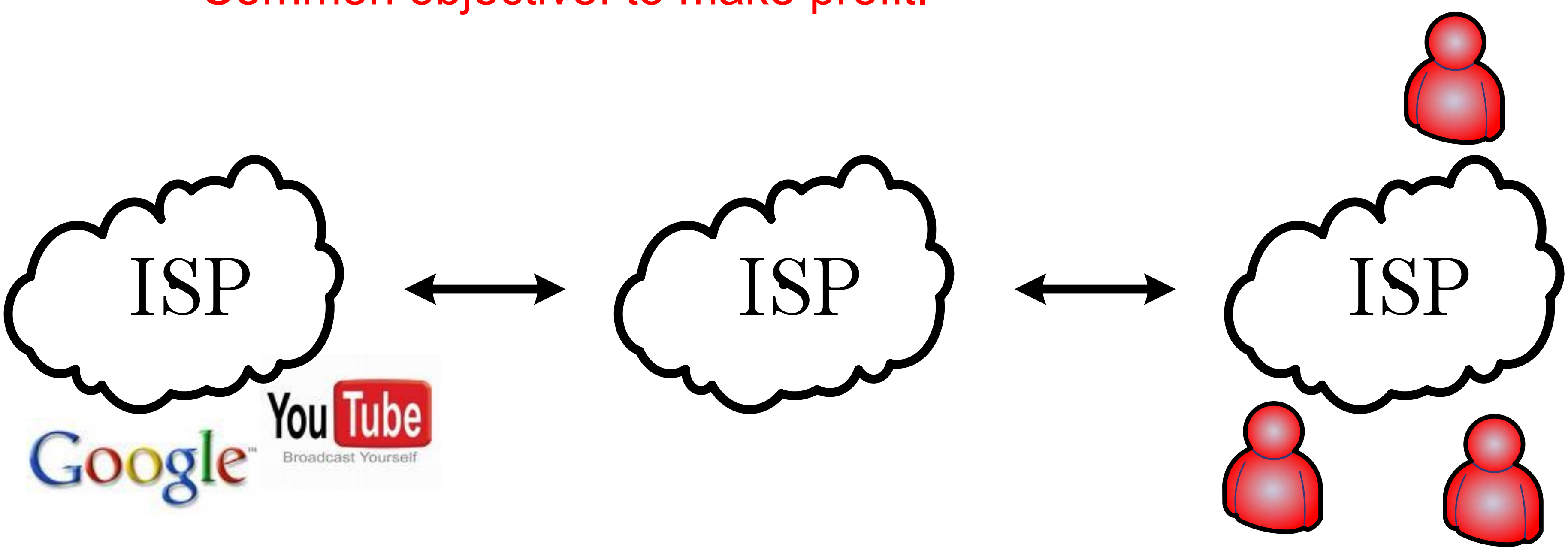
Outline

- The ISP settlement problem
- Shapley values and what they tell us

Building blocks of the Internet: ISPs

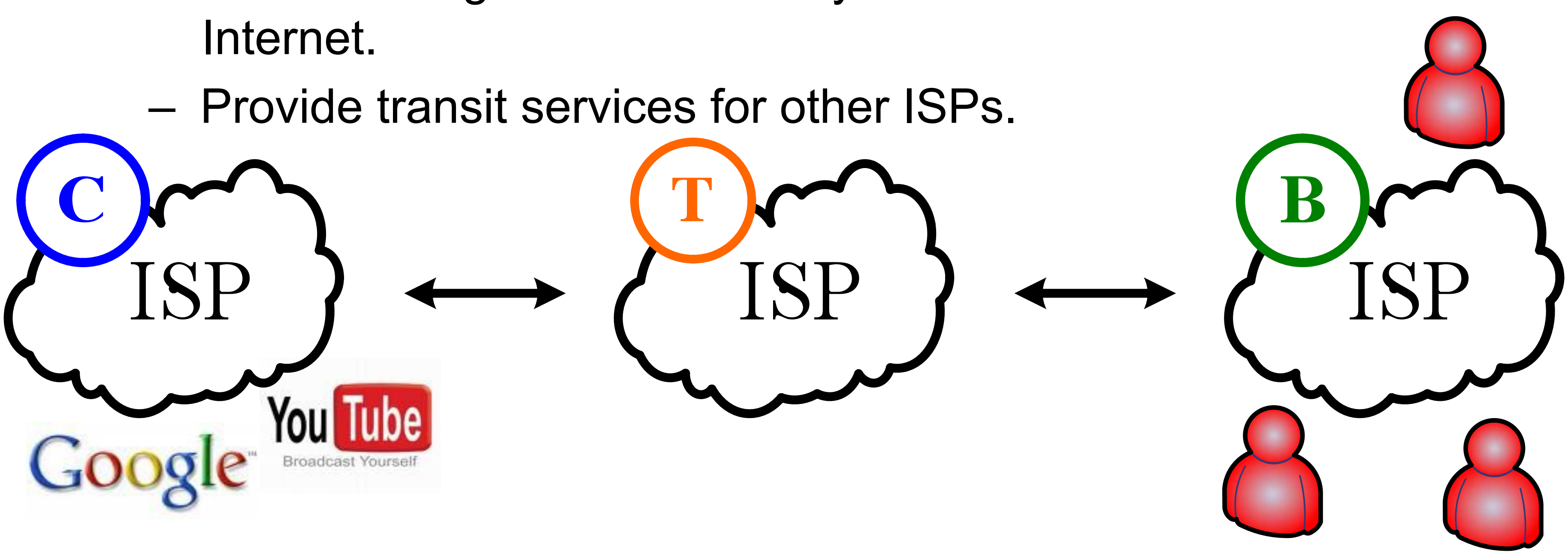
- The Internet is operated by hundreds of interconnected Internet Service Providers (ISPs).

- An ISP is a autonomous business entity
  - Provide Internet services.
  - Common objective: to make profit.



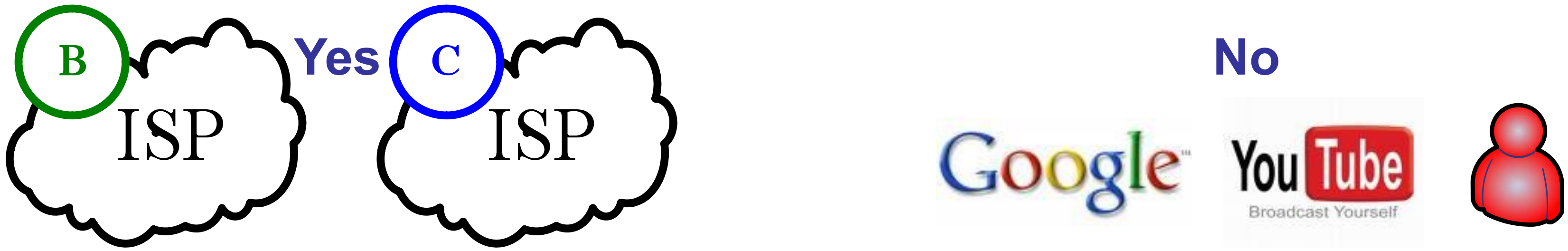
Three types of ISPs

- **Eyeball ISPs:**
  - Provide Internet access to individual users.
  - E.g. TimeWarner, Free
- **Content ISPs:**
  - Provide contents on the Internet.
- **Transit ISPs:**
  - Tier 1 ISPs: global connectivity of the Internet.
  - Provide transit services for other ISPs.



Two important issues of the Internet

1. Network Neutrality Debate: Content-based *Service Differentiation* ?

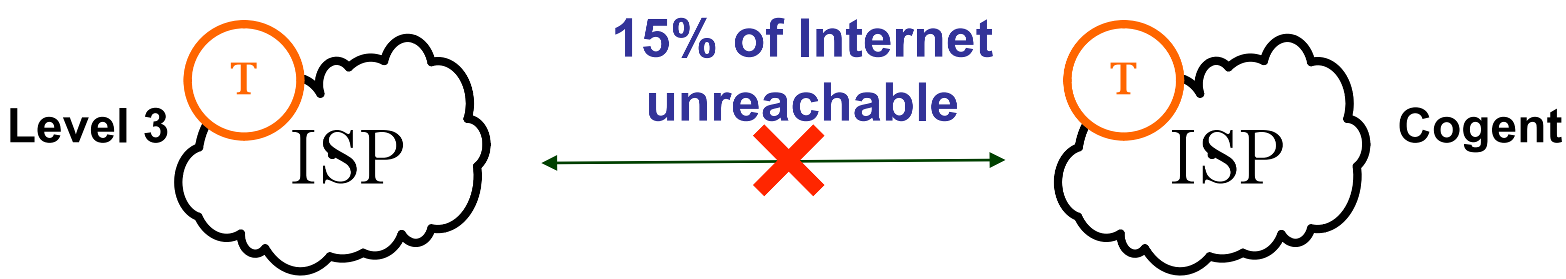


Legal/regulatory policy for the Internet industry: Allow or Not?

Allow: ISPs might dominate; Not allow: ISPs might die.

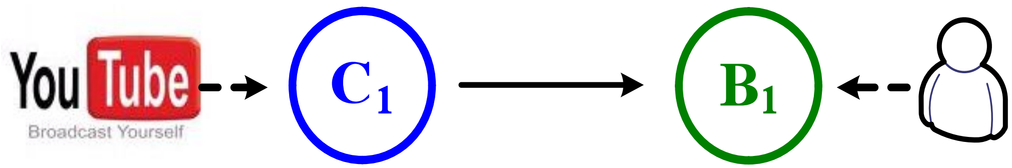
Either way, suppress the development of the Internet.

2. Network Balkanization: Break-up of connected ISPs



Not a technical/operation problem, but an economic issue of ISPs.
Threatens the global connectivity of the Internet.

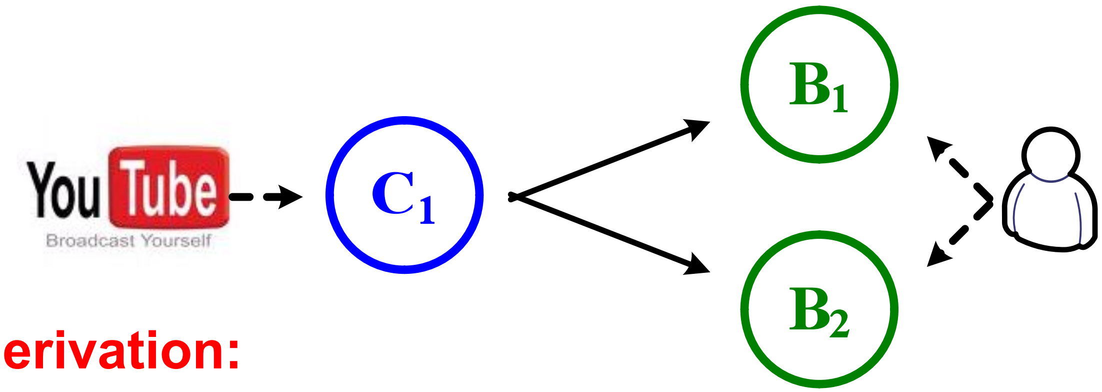
How does one share profit? -- the baseline case



- One content and one eyeball ISP
- Profit **V** = total revenue = content-side + eyeball-side
- Win-win/fair profit sharing:

$$\varphi_{B_1} = \varphi_{C_1} = \frac{1}{2} V$$

How do we share profit? – two symmetric eyeball ISPs



Axiomatic derivation:

- Symmetry: same profit for symmetric eyeball ISPs

$$\varphi_{B_1} = \varphi_{B_2} = \varphi_B$$

- Efficiency: summation of individual ISP profits equals v

$$\varphi_{C_1} + 2\varphi_B = V$$

- Fairness: same mutual contribution for any pair of ISPs

$$\varphi_{C_1} - \frac{1}{2}V = \varphi_{B_1} - 0$$

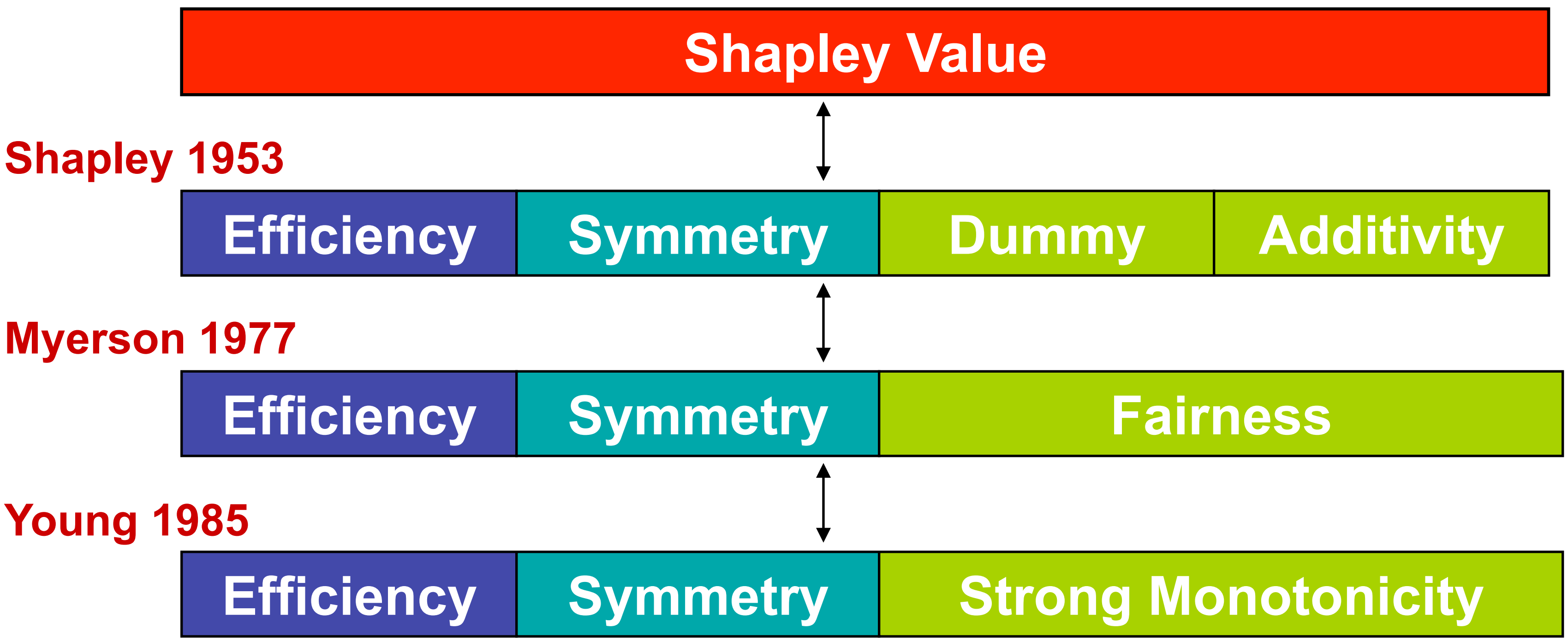
Unique solution (Shapley value)

$$\varphi_{C_1} = \frac{2}{3}V$$

$$\varphi_B = \frac{1}{6}V$$

History and properties of the Shapley value

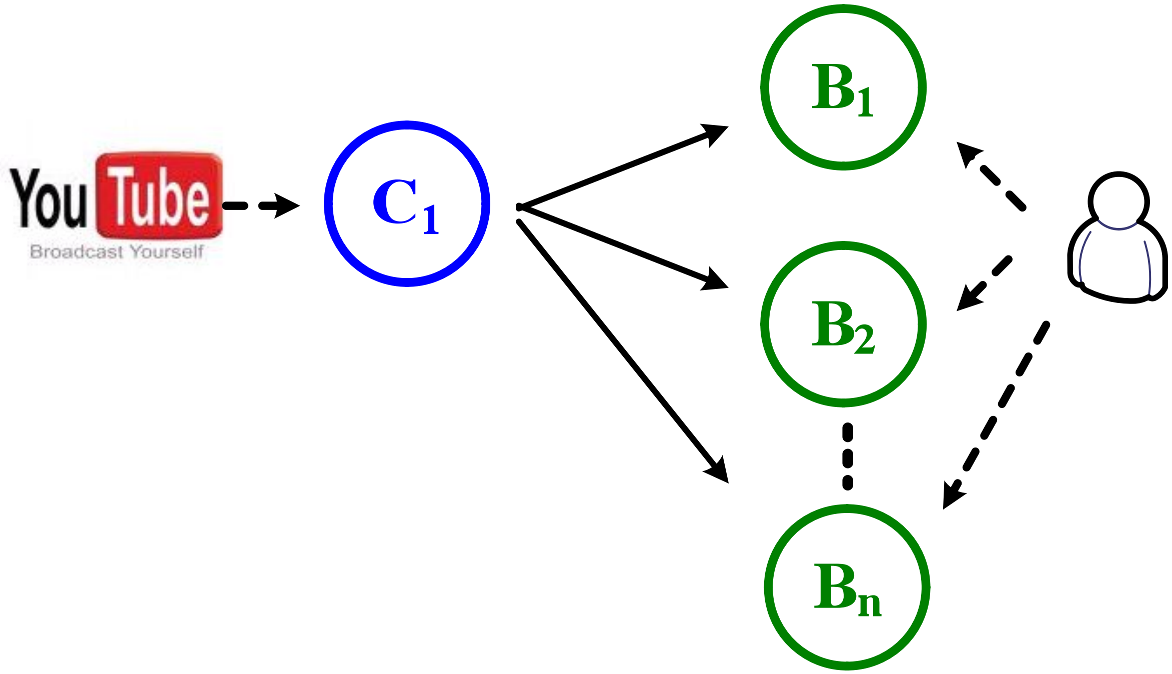
What is the Shapley value? – A measure of one's contribution to different coalitions that it participates in.



Shapley Values and Core

- Core. It is a solution concept that assigns to each cooperative game the set of payoffs that no coalition can improve upon or block.
- Convex Games: Whole is bigger than the sum of parts.
- The Shapley value of a convex game is the center of gravity of its core.

How do we share profit? -- n symmetric eyeball ISPs

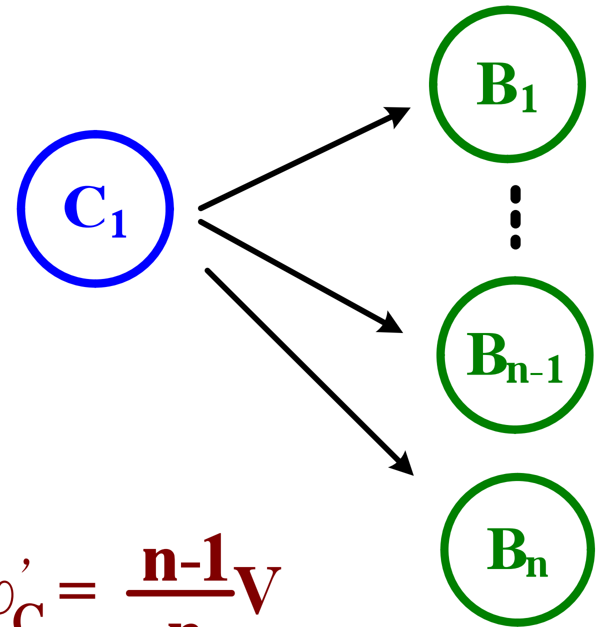


- Theorem: the Shapley profit sharing solution is

$$\varphi_B = \frac{1}{n(n+1)} V, \quad \varphi_C = \frac{n}{n+1} V$$

Results and implications of profit sharing

$$\varphi_B = \frac{1}{n(n+1)} V, \ \varphi_C = \frac{n}{n+1} V$$



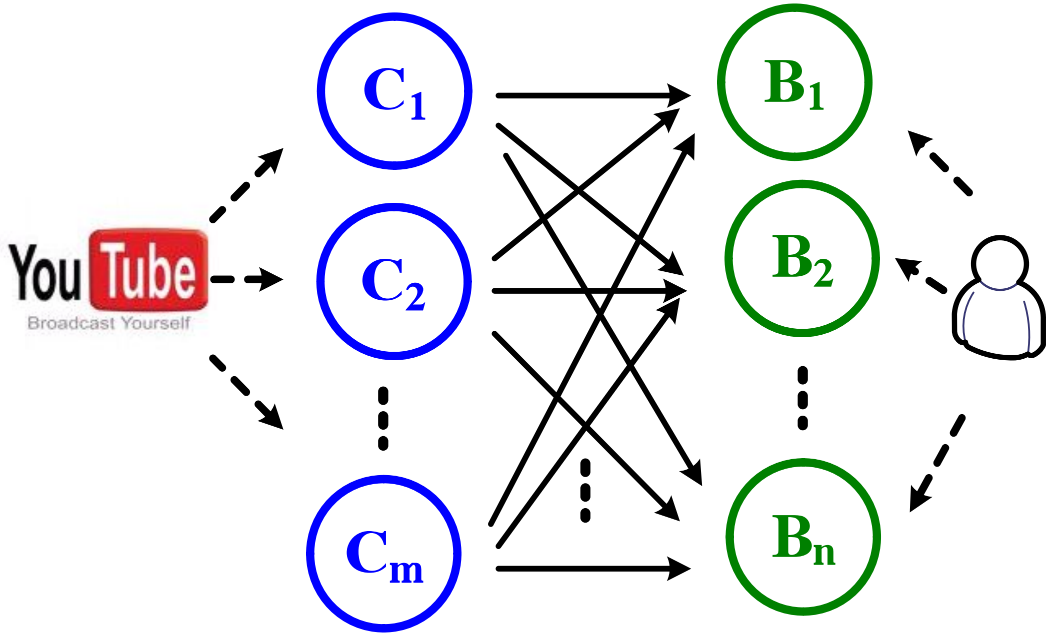
- More eyeball ISPs, the content ISP gets larger profit share.
  - Users may choose different eyeball ISPs; however, must go through content ISP,
  - Multiple eyeball ISPs provide redundancy,
  - The single content ISP has leverage.
- Content's profit with one less eyeball: $\varphi_C' = \frac{n-1}{n} V$
- The marginal profit loss of the content ISP:

$$\Delta\varphi_C = \frac{n-1}{n} V - \frac{n}{n+1} V = -\frac{1}{n^2} \varphi_C$$

If an eyeball ISP leaves

- The content ISP will lose $1/n^2$ of its profit.
- If n=1, the content ISP will lose all its profit.

Profit share -- multiple eyeball and content ISPs

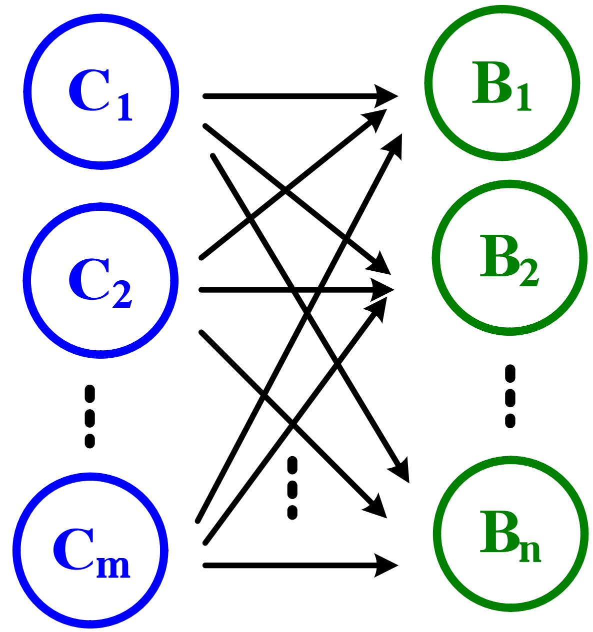


- Theorem: the Shapley profit sharing solution is

$$\varphi_B = \frac{m}{n(n+m)}V, \quad \varphi_C = \frac{n}{m(n+m)}V$$

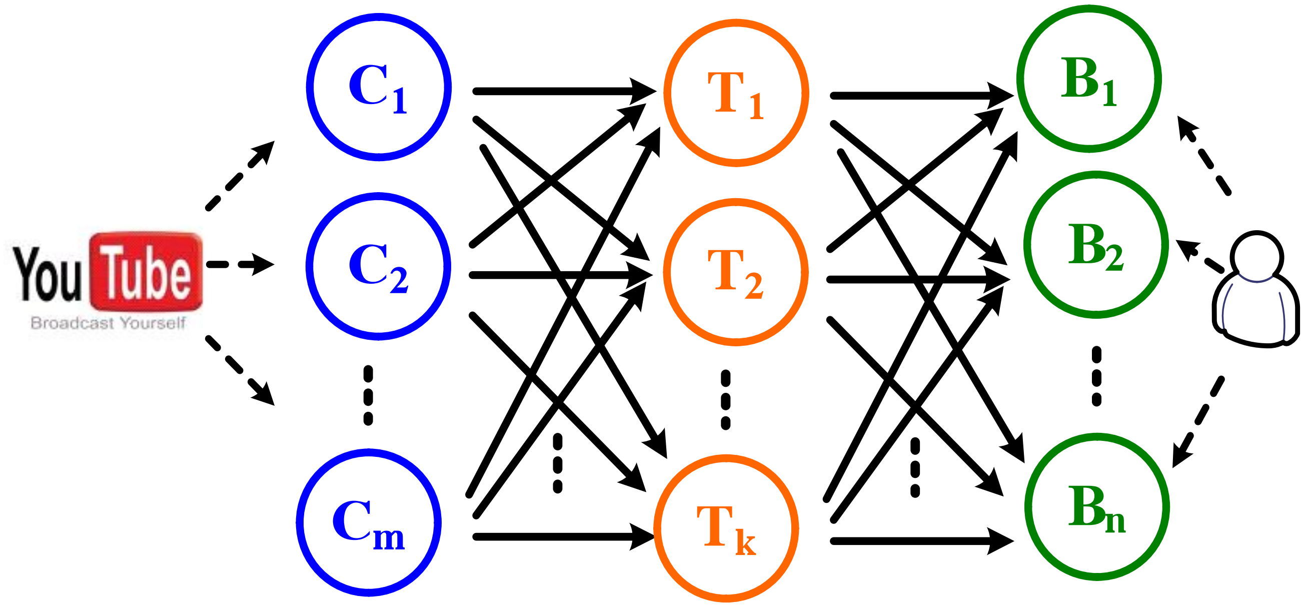
Results and implications of ISP profit sharing

$$\varphi_B = \frac{m}{n}\frac{V}{(n+m)}, \varphi_C = \frac{n}{m}\frac{V}{(n+m)}$$



- **Each ISP's profit share is**
  - Inversely proportional to the number of ISPs of its own type.
  - Proportional to the number of ISPs of the opposite type.
- **Intuition**
  - The larger group of ISPs provides redundancy.
  - The smaller group of ISPs has leverage.

Profit share -- eyeball, transit and content ISPs



- Theorem: the Shapley profit sharing solution is

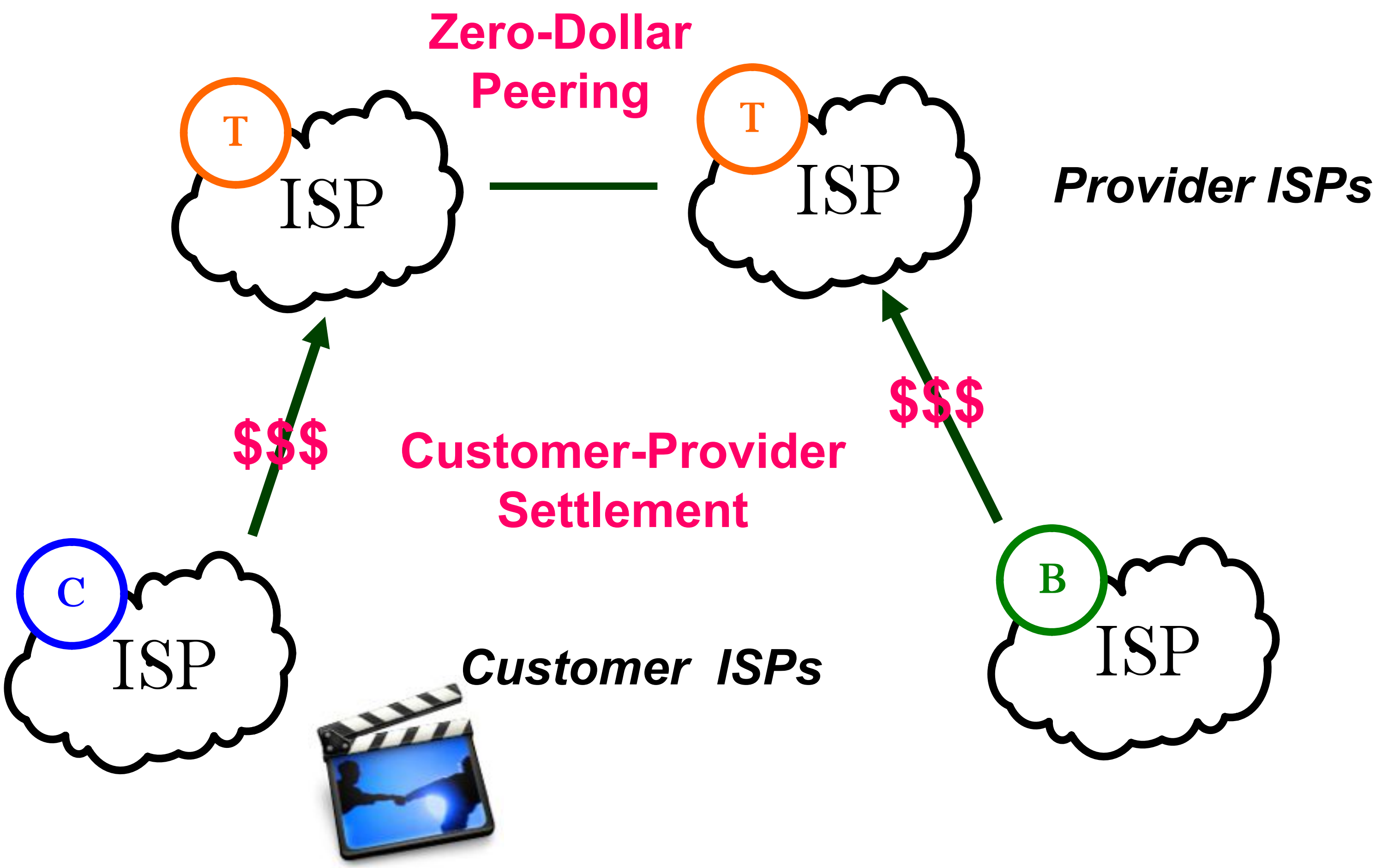
$$\varphi_B = \frac{V}{n+m+k} \sum_{\mu=1}^{m} \sum_{\kappa=1}^{k} \binom{m}{\mu} \binom{k}{\kappa} \binom{n+m+k-1}{\mu+\kappa}$$

$$\varphi_C = \frac{V}{n+m+k} \sum_{\nu=1}^{n} \sum_{\kappa=1}^{k} \binom{n}{\nu} \binom{k}{\kappa} \binom{n+m+k-1}{\nu+\kappa}$$

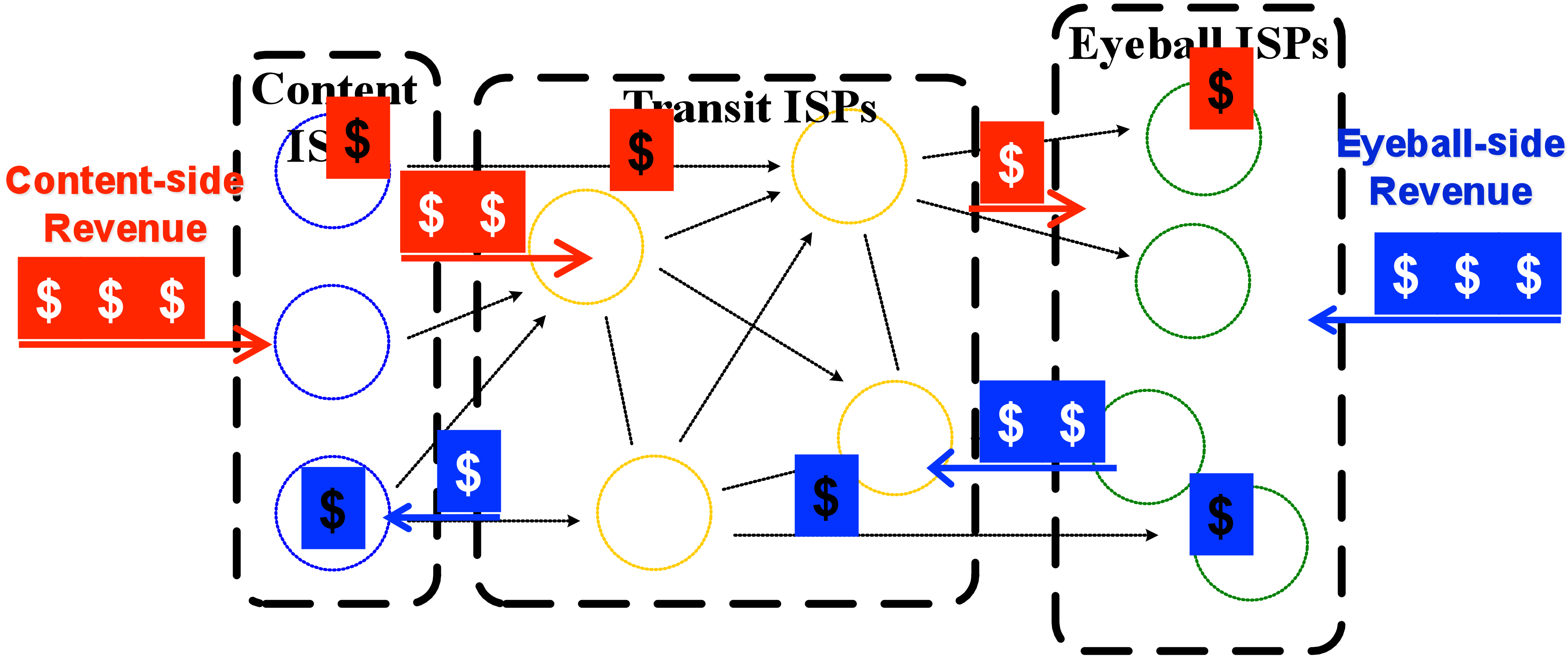
$$\varphi_T = \frac{V}{n+m+k} \sum_{\mu=1}^{m} \sum_{\nu=1}^{n} \binom{m}{\mu} \binom{n}{\nu} \binom{n+m+k-1}{\mu+\nu}$$

Current ISP Business Practices: A Macroscopic View

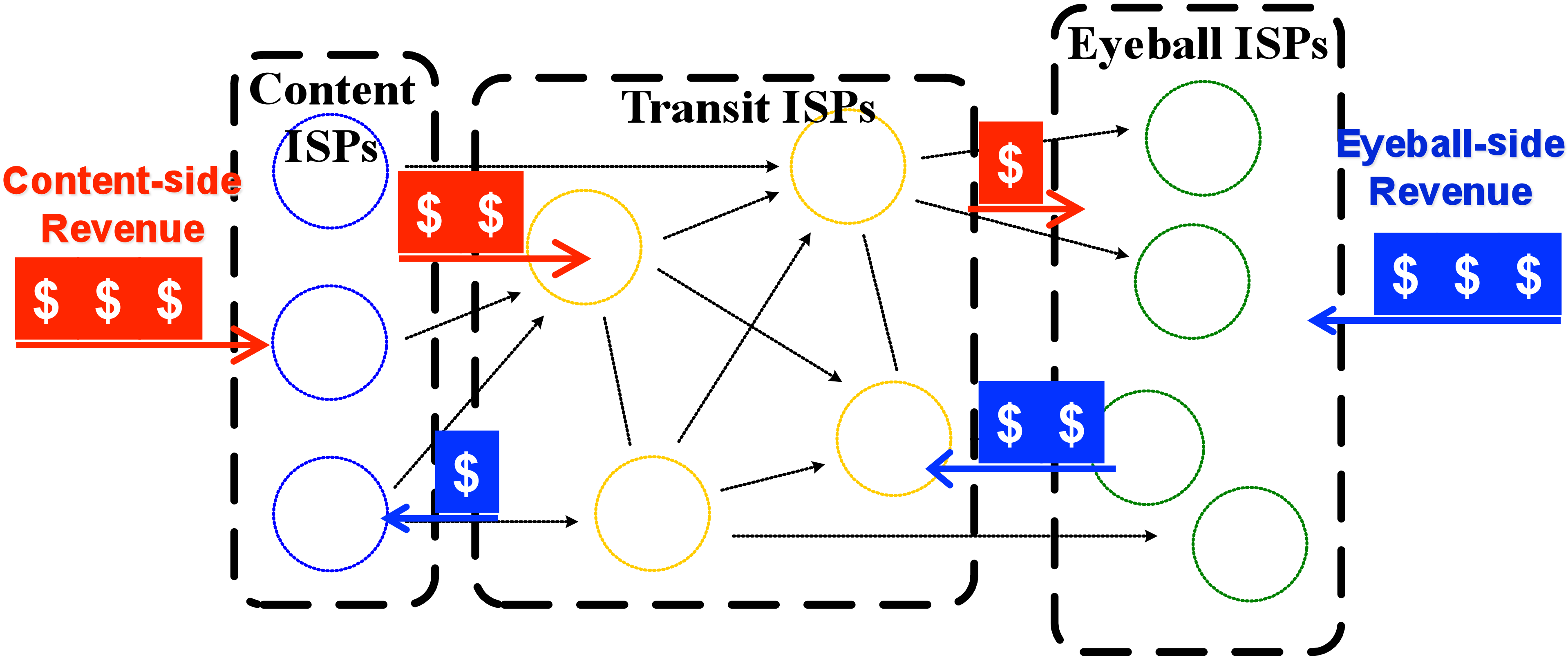
Two forms of bilateral settlements:



Achieving the "Shapley solution"

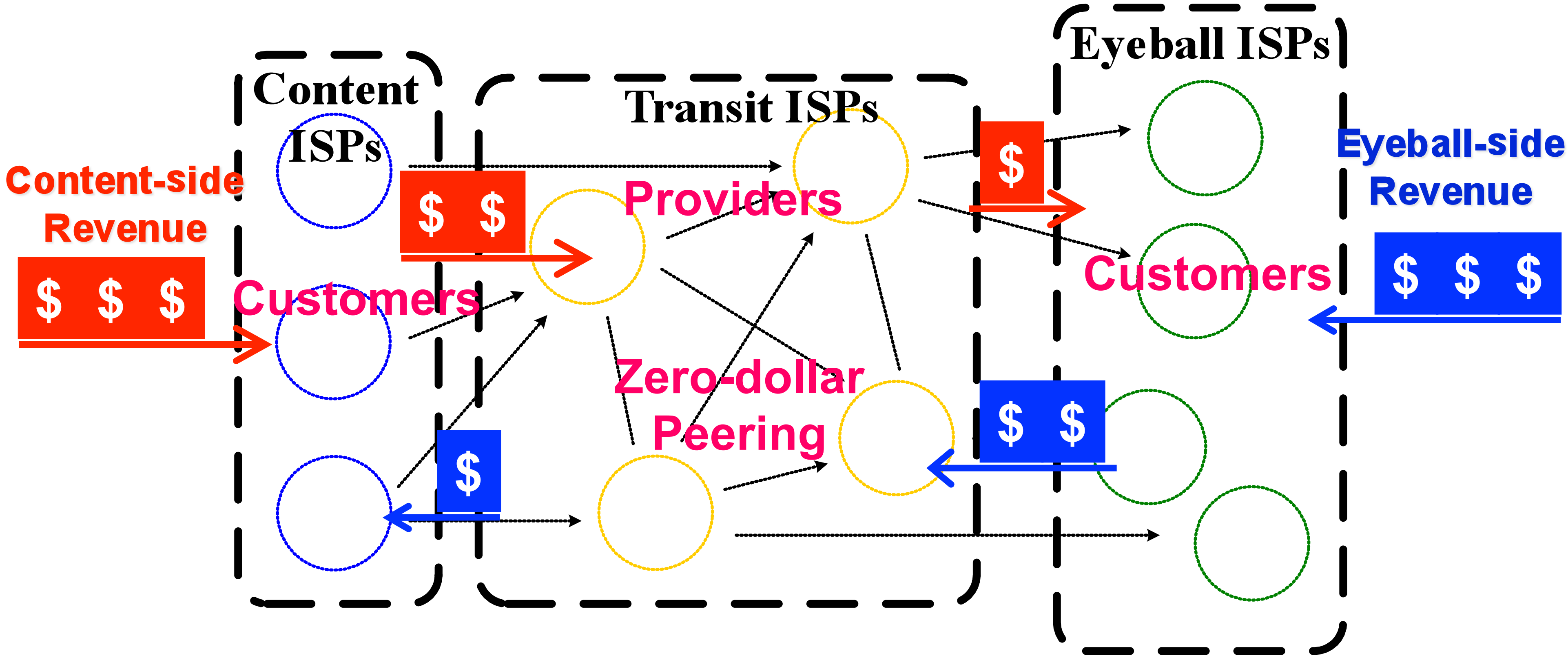


Achieving the "Shapley solution"



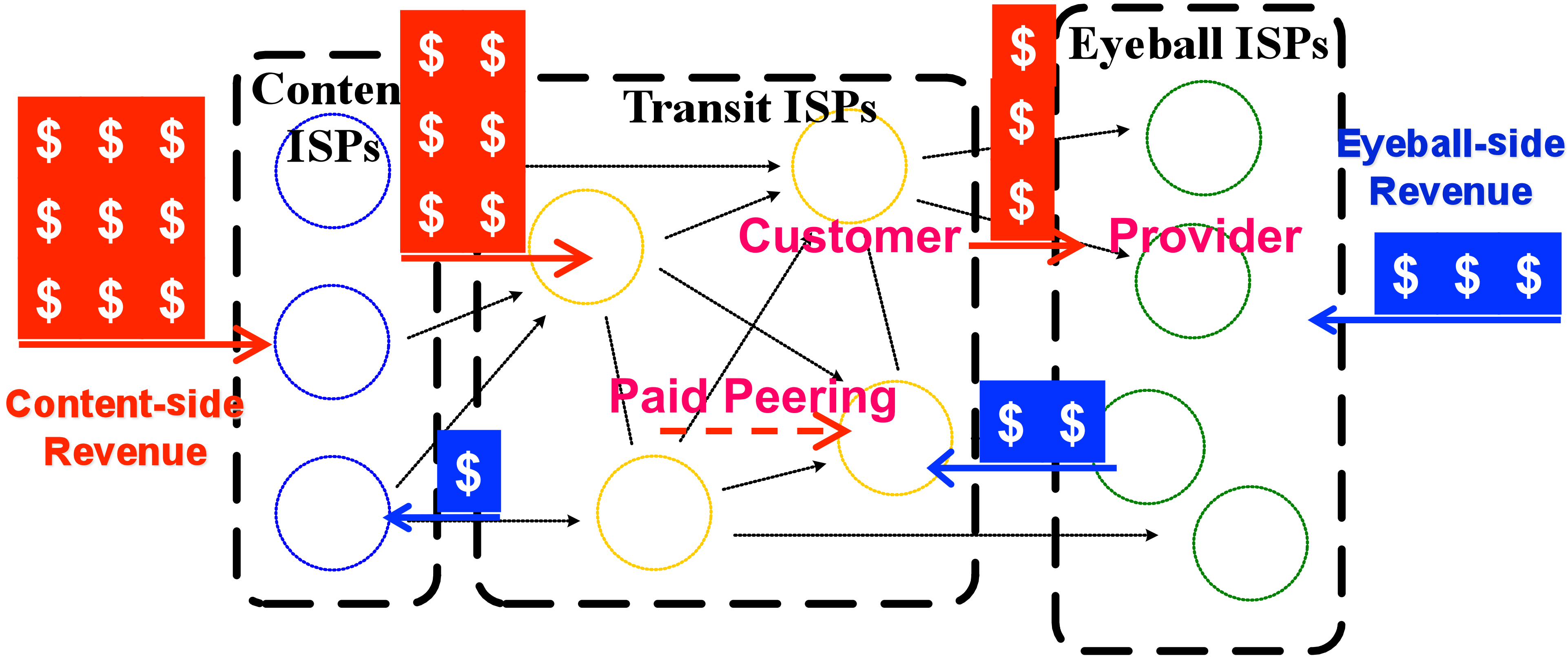
- Two revenue flows to achieve the Shapley profit share:
  - Content-side revenue: Content →Transit →Eyeball
  - Eyeball-side revenue: Eyeball →Transit →Content

Achieving Shapley solution by bilateral settlements



- When CR ≈ BR, bilateral implementations:
  - Customer-Provider settlements (Transit ISPs as providers)
  - Zero-dollar Peering settlements (between Transit ISPs)
  - Current settlements can achieve fair profit-share for ISPs.

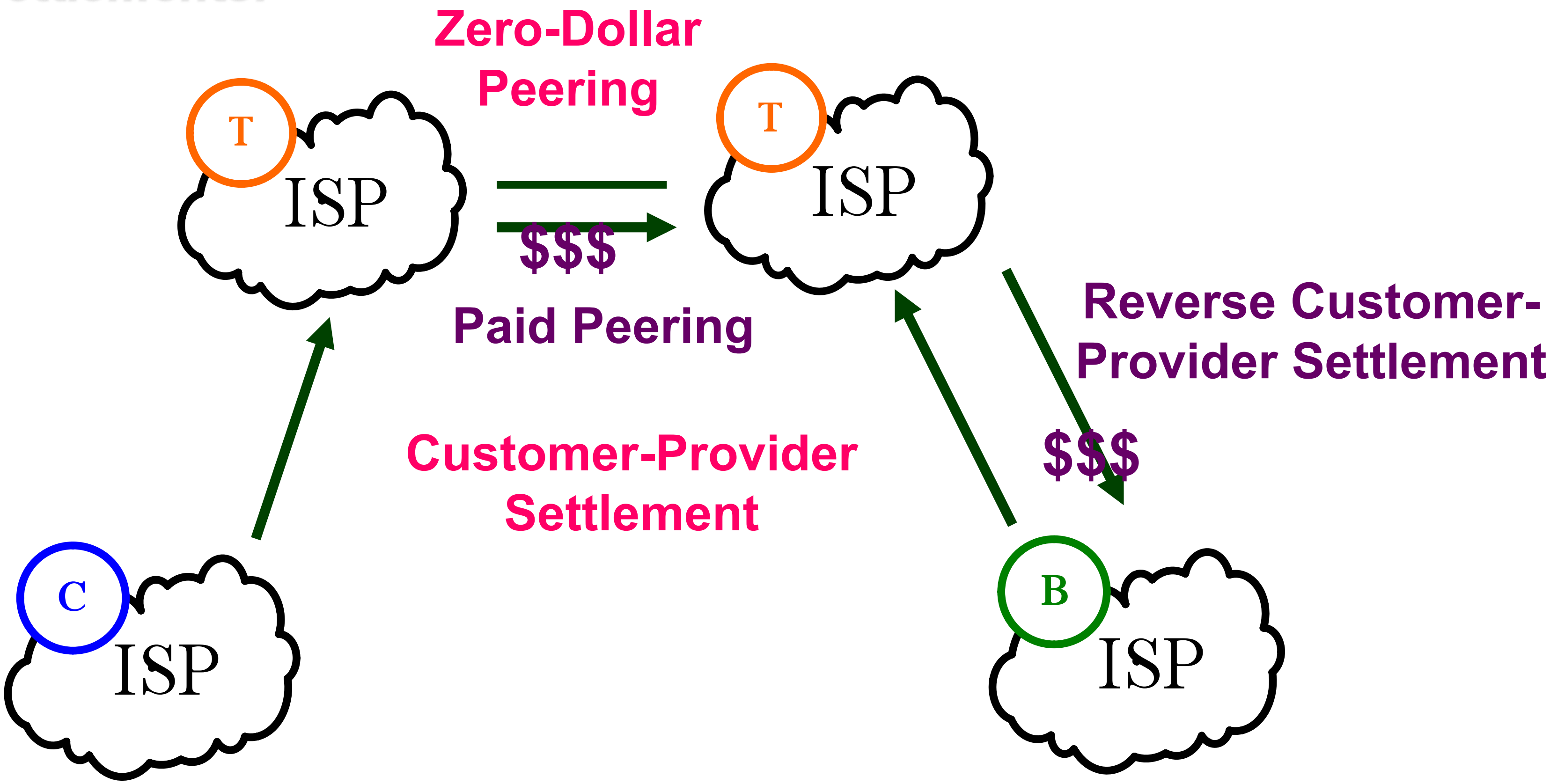
Achieving Shapley solution by bilateral settlements



- If CR >> BR, bilateral implementations:
  - *Reverse Customer-Provider* (Transits compensate Eyeballs)
  - *Paid Peering* (Content-side compensates eyeball-side)
  - New settlements are needed to achieve fair profit-share.

Recap: ISP Practices from a Macroscopic View

Our Implication: Two additional forms of bilateral settlements:



Imbalances

- At the network layer: flat rate vs. volume based charge
  - Encouraging companies like People CDN
  - "Light" eyeball users cross subsidizing heavy hitters

- At the application layer: Google/EBay/Amazon profits vs. ISP profits
  - Network Neutrality?
  - Commoditization of end-to-end bandwidth vs. local monopolies

Ongoing work

- Data gathering to verify (presence and/or level of) imbalances
- Introducing P2P into the mix

Related Publications

- Richard T.B. Ma, Dahming Chiu, John C.S. Lui, Vishal Misra and Dan Rubenstein, **On Cooperative Settlement Between Content, Transit and Eyeball Internet Service Providers,** ***Proceedings of 2008 ACM Conference on Emerging network experiment and technology (CoNEXT 2008), Madrid, Spain, December, 2008***

- Richard T.B. Ma, Dahming Chiu, John C.S. Lui, Vishal Misra and Dan Rubenstein, **The Shapley Value: Its Use and Implications on Internet Economics,** ***Allerton Conference on Communication, Control and Computing, September, 2008***

- Richard T.B. Ma, Dah-ming Chiu, John C.S. Lui, Vishal Misra and Dan Rubenstein, **Interconnecting Eyeballs to Content: A Shapley Value Perspective on ISP Peering and Settlement,** ***ACM NetEcon, Seattle, WA, August, 2008***

- Richard T.B. Ma, Dahming Chiu, John C.S. Lui, Vishal Misra and Dan Rubenstein, **Internet Economics: The use of Shapley value for ISP settlement,** ***Proceedings of 2007 ACM Conference on Emerging network experiment and technology (CoNEXT 2007), Columbia University, New York, December, 2007***

The Shapley value mechanism φ

$$\varphi_i = \frac{1}{N!} \sum_{\pi \in \Pi} \Delta_i (S(\pi, i))$$

N: total # of ISPs, e.g. N=3

Π: set of N! orderings

S(π,i): set of ISPs in front of ISP i